Review of the concept of nuclear fusion energy, and the ITER international experiment

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Section 1: What is nuclear fusion?

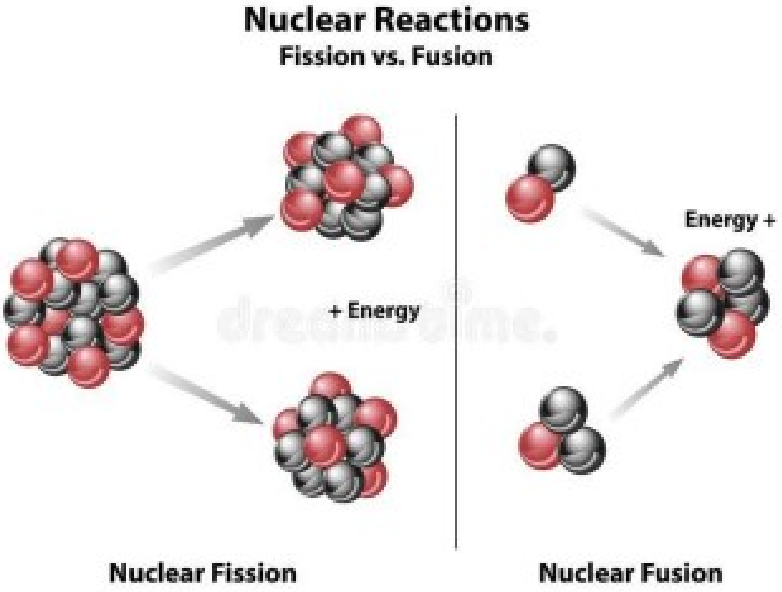

Fig. 1: The elementary reactions of nuclear fusion and nuclear fission
Source: https://www.dreamstime.com/fusion-fission-compared-reactions-nuclear-diagram-molecular-form image193847312#res26615551 (Dreamtime, 2022)

Nuclear fission and nuclear fusion are nuclear reactions which can be used to extract energy from the nucleus. Nuclear fission is when a neutron is directed to an atom with force, splitting the atom into two new ones. When the atoms are split, great amount of energy is released. Additional neutrons are released in the reaction that cause a chain reaction, making the atoms split further. On the contrary, nuclear fusion forces two atoms together to create a new, heavier atom. When the atoms are joined, energy is released, although for this reaction tremendous amount of heat is necessary. Fusion is the same process that powers the sun, but scientist have been struggling recreating the process due to the tremendous amounts of pressure and temperature needed.

Section 2: Magnetic confinement fusion, and difference with respect to inertial fusion.

The difference between inertial fusion and magnetic-confinement fusion: Inertial-confinement fusion is done by slamming a fusion target (such as a pellet containing deuterium and tritium) with the beams from an array of extremely-high-energy devices, such as lasers or X-rays. The beams heat the fuel to temperatures high enough for fusion to occur, in a time interval small enough to prevent the gases from spreading out too much before the reaction can happen.

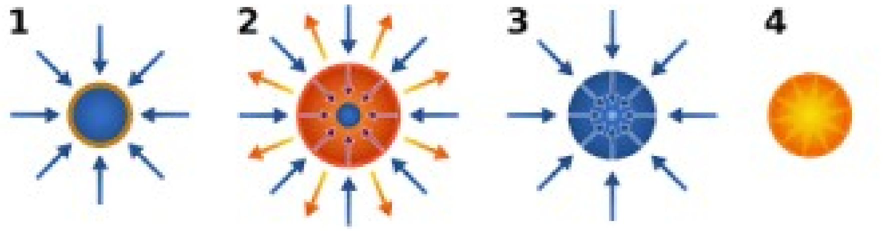

Fig 2: The four phases of inertial confinement fusion.
Source: https://fr.m.wikipedia.org/wiki/Fichier:Inertial_confinement_fusion.svg

Magnetic confinement fusion uses high-strength magnetic fields to contain a hot plasma of fusion fuel. Since the plasma would cool too much if it touched the reactor walls (and since the walls would be damaged by the contact), it must be prevented from such contact. Some magnetic confinement concepts exploit the fact that plasma is electrically conductive, so a current can be established within it. The magnetic field of this current interacts with the fields of magnets that surround the chamber, causing the plasma to constrict itself away from the walls.

Fig. 3. The two main concepts of magnetic confinement fusion: a stellarator (left) and a tokamak (right)
Source: https://www.iaea.org/fr/energie-de-fusion/la-fusion-par-confinement-magnetique-tokamaks-et-stellara tors

The magnetic confinement concept employs a large magnetic field to confine the movement of deuterium–tritium plasma. The magnetic field prevents the particles from coming into contact with the reactor walls, which will dissipate the heat of the nuclei and slow down its movement. One of the most effective magnetic configurations is a doughnut-shaped toroid in which the magnetic field is curved around to form a closed loop. This configuration takes the name of Tokamak.

Source: https://www.sciencedirect.com/topics/engineering/magnetic confinement#:~:text=The%20magnetic%20confinement%20concept%20employs,and %20slow% 20down%20its%20movement.

Section 3: The fuel of nuclear fusion

Deuterium & Tritium origin

Deuterium and Tritium are hydrogen isotopes that will be used in the fusion reactor. Deuterium is easily accessible in unlimited quantities in the ocean water, whereas tritium is limited and harder to extract (ITER, 2022).

Tritium can be artificially produced in nuclear reactors with lithium. For the ITER project, approximately 20 kg tritium will be used that was produced by a CANDU-type nuclear reactor (ITER, 2022). This is also the global inventory of tritium and therefore finding another source for this fuel material is essential for the future of fusion. In the later stages of fusion, the DEMO demonstration, the tritium production will have to be self-sufficient as external sources will not be sufficient for the amount needed to produce the daily produced energy.
Therefore ITER is also experimenting with development of a prototype of lithium blankets in a fusion environment for future lithium production (see Sec. 4). (ITER, 2022). Production of tritium can be made by interaction between the neutrons released from the plasma together with lithium (ITER, 2022). This will mean that for future nuclear fusion companies will not need external suppliers for the tritium material as it will be self-sufficient within the fusion reactor.

The extraction of deuterium from ocean water is simple and used in industrial processes. First water where the deuterium substitutes the hydrogen (D20) is separated from regular water through a chemical exchange process and then is submitted to electrolytes to obtain deuterium gas (ITER, 2022). Deuterium is easily accessible and not harmful, therefore there is no ongoing research to make deuterium self-sufficient.

Fig. 4. *Illustration of the blanket*
Source : https://www.iter.org/mach/Blanket (ITER, 2022)

References

Fuelling the fusion Reaction. (n.d). ITER. Retrieved March 22, 2022, from https://www.iter.org/sci/FusionFuels
Production dutritium. (n.d.). ITER. Retrieved March 22, 2022, from https://www.iter.org/fr/mach/tritiumbreeding

Section 4: Would nuclear fusion be a renewable energy source? Would it be sustainable?

Fig. 5. An artist's impression of the European fusion power plant design
Source : https://www.iter.org/sci/Fusion

A renewable energy is defined as an energy which can last forever. A non-renewable resource can be sustainable if it is used at a slow enough rate that supplies last for thousands of years and environmental impacts do not cause huge problems.

Fusion fuels are widely available and nearly inexhaustible. Deuterium can be distilled from all forms of water, while tritium will be produced during the fusion reaction as fusion neutrons interact with lithium.

Deuterium and tritium are used for both MCF and ICF and they are both renewable. On the other hand, terrestrial reserves of lithium are not infinite but they would permit the operation of fusion power plants for more than 1,000 years (while sea based reserves of lithium would fulfil needs for millions of years).

Source: https://www.forbes.com/sites/jamesconca/2016/03/24/is-nuclear-power-a-renewable-or-a-sustainable-energy-source/?sh=49ce9395656e

Therefore, nuclear fusion can be labelled as non-renewable but sustainable source of energy.

How many years we can continue using fossil fuels at relatively low prices?

According to research based on 2015 data, the current statement of when our reserves will be emptied is this:

Oil: 51 years
Coal: 114 years
Natural gas: 53 years

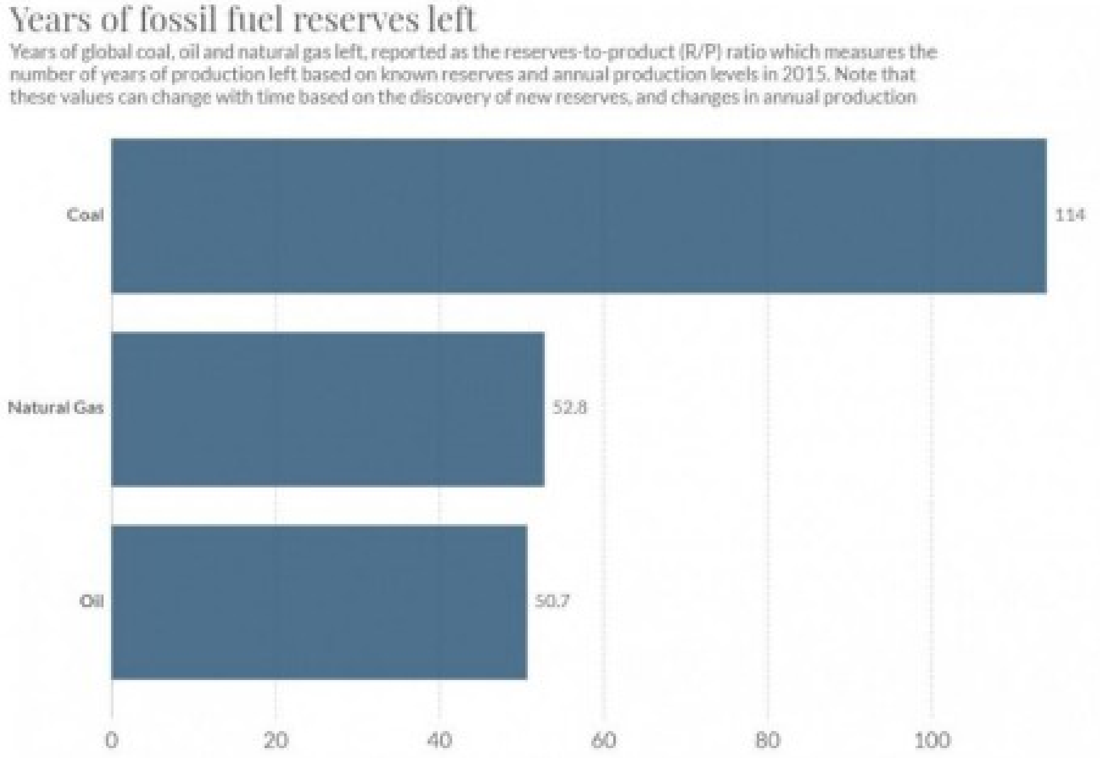

Fig. 6. Years of fossil Fuel Reserves left

Other sources estimate that we will run out of fossil fuels much earlier – for example, oil deposits will be gone by 2052. We do not just have to reduce our consumption of fossil fuels and switch to green energy because we run out of supplies, but also because coal and oil are harming our environment badly.

Source: https://group.met.com/en/mind-the-fyouture/mindthefyouture/when-will-fossil-fuels-run-out

How many years we can continue using nuclear fission at relatively low prices? Steve Fetter, dean of the University of Maryland's School of Public Policy, supplies an answer: “If the Nuclear Energy Agency (NEA) has accurately estimated the planet's economically accessible uranium resources, nuclear fission reactors could run more than 200 years at current rates of consumption.” But currently, nuclear fission represents a small percentage of the total consumption. This means that, in any case, other sources of energy should be found in the next decades, to substitute fossil fuels (presently representing the dominant energy sources).

Source: https://www.scientificamerican.com/article/how-long-will-global-uranium-deposits-last/

Section 5: Would nuclear fusion be a clean energy source?

Radioactivity of the materials compared to nuclear fission

In fission, radioactive materials are used, and after the fission, reaction particles are released together with gamma rays (EDP sciences, 2022). These particles are referred to as “fission products”. The fission products are often very unstable and more radioactive than the initial material used as fuel for the fission. Often used fission fuel is the material uranium which is somewhat radioactive (EDP sciences, 2022).

In fusion, tritium and deuterium are used. The level of radioactivity is much higher in tritium than in uranium which is used in fission. In the deuterium-tritium fusion reaction, there are no radioactive products as a result. Instead neutrons are released together with helium atoms (ITER, 2022). During operation fusion reactor components will be exposed to long periods of neutron irradiation. As such, a reactor’s structural steels will become activated and need to be disposed of as radioactive waste. Previous studies have shown that such wastes can struggle to meet low level waste (LLW) requirements meaning that costly geological disposal may be required (Bailey, 2021).

Because fusion does not have any radioactive bi-products from the reaction, it indicates that the fusion does not directly create harmful waste, unlike the fission reaction. Fission products are often very unstable due to the high neutron number and the products tend to undergo beta decay leading to the reaction having additional release of radiation even after the reaction is done.

The half life of tritium is 12.3 years whereas the half life of Uranium-238 is 4.5 billion years. The produced fission products commonly have a half life that is short or medium lived, ranging from 5- 100 years. If a material has longer half life it indicates that the radioactivity level is less (EDP sciences, 2022).
The European Union is currently holding research and training conferences to develop solutions to the nuclear risks and wastes. The conferences are divided in two: radioactive waste management (EURADWASTE ‘22) and fission safety on reactor systems (FISA ‘22). Some of the objectives for these conferences are to share updated information and achievements received by the 80 projects that have been done since the conference held 2019, reward relevance and excellence that is performed in nuclear research and interact in discussions, exhibitions, and matchmaking interviews (sfem, 2022).

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Section 6: Would nuclear fusion be a safe energy source?

Risks of explosion compared to nuclear fission

Fission reaction is located in a nuclear fission reactor. A heavy atom splits and left are two atoms with a combined mass lighter than the initial atom, the excess mass is converted to energy (Becker, 2017). The reaction then initiates further atoms to do the same. The reaction is exponentially growing and in a nuclear reactor it is controlled carefully. If it is not properly controlled, it can be dangerous due to the high risk of explosion because of the high energy release (Becker, 2017). Fission is basically a controlled chain reaction that emits high energy and radioactivity and can be potentially dangerous if not controlled. In an uncontrolled state of fission, heat, radiation and force is released on a regional scale.

On the contrary, fusion is not a chain reaction, instead it is a reaction between two materials in high heat (IAEA, 2022). To maintain the reaction, sufficient heat needs to be applied to keep the stage of the plasma, if faults appear in the machines the plasma cools down and the reactor stops with no external effects (IAEA, 2022). In this manner, fusion is expected to be safer than fission because if the energy companies experience disturbances internally or externally, fusion reactions don't face the same risks of consequences as fission reactions do.

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https://www.iaea.org/topics/energy/fusion/faqs

Section 7: What is the present financial engagement for fusion, and how is it compared to other international projects?

Funding of ITER

ITER is being developed, built and operated as a joint research project by the seven equal partners, the EU, representing the 27 EU states, the United Kingdom and Switzerland, the USA, China, South Korea, Japan, Russia and India. The USA had temporarily withdrawn from the project from 1998 to 2003, and Canada has not been involved since 2004. (Wikipedia page on ITER, 2003)

Current Budget

The current budget of the ITER Project is $25 Billion. (Ball, 2021). During the construction phase of the project, Europe has responsibility for approximately 45.5 percent of construction costs, whereas China, India, Japan, Korea, the Russian Federation and the United States will contribute approximately 9.1 percent each. The lion's share (90 percent) of contributions will be delivered "in-kind." That means that in the place of cash, the Members will deliver components and buildings directly to the ITER Organization. (ITER, 2020)

The in-kind contributions of the ITER Members have been divided into approximately 140 Procurement Arrangements. These documents detail the technical specifications and management requirements for the procurement of plant systems, components or site construction. The value of each Procurement Arrangement is expressed in ITER Units of Account (IUAs), a currency devised to measure the value of in-kind contributions to ITER consistently over time. (ITER, 2020)

Procurement allocations were assigned among the Members on the basis of valuations of components. Upon successful completion of a component, the corresponding credit value is credited to the Members' account. Contributing 9.1 percent of the project, therefore, becomes a matter of adding up the IUA value of the different contributions. (ITER, 2020)

For the operation phase, the sharing of cost among the Members will be as follows: Europe 34 percent, Japan, and the United States 13 percent, and China, India, Korea, and Russia 10 percent. (ITER, 2020)

Alternative concepts to ITER

As you can see in the chart below (Chart 1), there are many other companies, which want to achieve the same goal as ITER. “Five companies are betting they can achieve controlled thermonuclear fusion a decade or more before the $25 billion international ITER project.” (David Kramer, Investments in privately funded fusion ventures grow,2020)

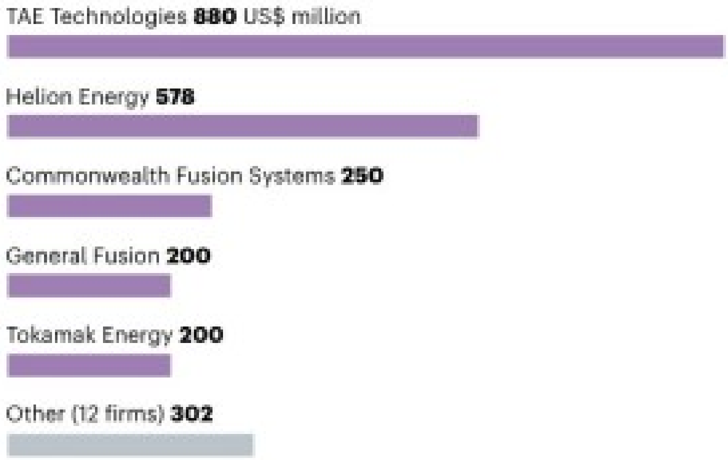

Fig. 7. Budgets of companies
Chart 1: Source: https://www.nature.com/immersive/d41586-021-03401-w/index.html

“Advocates of fusion technology say it has many parallels with the space industry” (Ball, 2021). Many of ITER's competitors listed in Chart 1 are active in the space industry. It has been recognized that nuclear fusion may be the future when it comes to producing energy. This is precisely why private companies are trying to outpace the ITER project.

NASA Budget

NASA's budget for financial year (FY) 2020 is $22.6 billion. It represents 0.48% of the $4.7 trillion the United States plans to spend in the fiscal year. Since its inception, the United States has spent nearly US$650 billion (in nominal dollars) on NASA.

ISS

As of 2010 the total cost was US$150 billion. This includes NASA's budget of $58.7 billion (inflation-unadjusted) for the station from 1985 to 2015 ($89.73 billion in 2021 dollars), Russia's $12 billion, Europe's $5 billion, Japan's $5 billion, Canada's $2 billion, and the cost of 36 shuttle flights to build the station, estimated at $1.4 billion each, or $50.4 billion in total. Assuming 20,000 person-days of use from 2000 to 2015 by two- to six-person crews, each person-day would cost $7.5 million, less than half the inflation-adjusted $19.6 million ($5.5 million before inflation) per person-day of Skylab.

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http://www.iter.org/faq#How_is_ITER_financed_

Section 8: Why are the difficulties still present in the path to nuclear fusion? An example of plasma instabilities.

Nowadays nuclear fusion is still an experimental Phase, as we do not have controlled fusion producing a net amount of energy in our laboratory. The main reason is that fusion fuel, which is in a state of plasma, usually presents turbulence and instabilities.

An example of instability in tokamak plasmas is given by Toroidal Alfvén eigenmodes (TAE). TAE are modes with shear-Alfvén wave (SAW) polarization, are transverse electromagnetic plasma oscillations propagating along the equilibrium magnetic field in magnetized plasmas. Tokamak plasmas often present a supra-thermal species, also named energetic particle (EP) due to external heating or to the product of fusion reactions. In tokamaks, TAE are important as they can effectively tap the free energy of the EP population, nonlinearly modifying the EP distribution, and therefore changing the efficiency of the heating mechanism [Chen. L., & Zonca, F., 2016].

Understanding the dynamics of TAEs in present tokamaks and predicting it in future experi ments like ITER, can help increasing the stability and confinement of fusion plasmas. TAEs can be identified in tokamak plasmas by means of experimental diagnostics and com pared with theoretical models. The frequency can be estimated as

1) $w^2 = {v_A}^2 k^2$

2) $k = \frac{1}{qR}(nq - m)$

Symbols: w = Frequency of the Shear Alfven wave, v_A = the Alfven speed, k = component of the wavenumber parallel to the equilibrium magnetic field, q = safety factor (it refers to the helicity of the equilibrium magnetic field) r (which plays the role of radial coordinates.) n = toroidal Mode number, m = the poloidal mode number.

So, we can get normalized frequency as

$$w_n = \frac{nq - m}{q} \qquad (W_n = \mathbf{W} \times \frac{R}{V_A})$$

Considering ASDEX Upgrade case discussed in reference [Vannini-2020], we can obtain this Frequency profile assuming n=1 and m = 2,3.

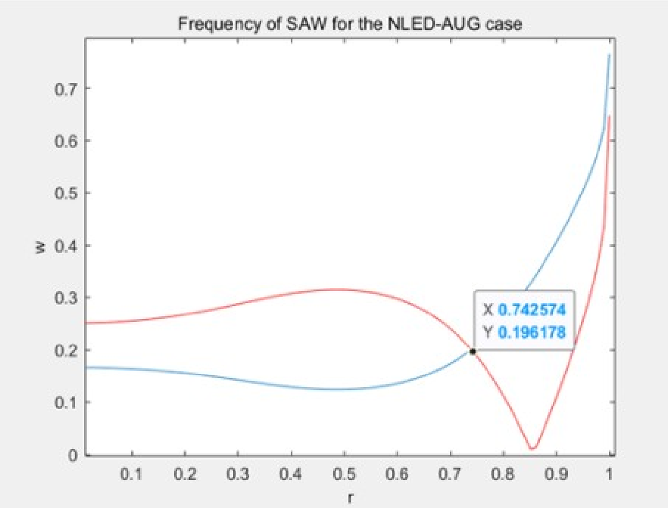

Fig. 8. Graph of frequency vs radius for NLED-AUG

We can estimate a normalized frequency of TAE of $W_n = 0.2$, corresponding to a frequency of the order of magnitude:

$$\boldsymbol{W_{TAE}} = 231\ \boldsymbol{KHz} \sim 10^5\ \mathbf{Hz}$$

which is in good agreement with the numerical and experimental measurements of [Vannini-2020].

Also considering ITER case discussed in reference [T. Hayward-Schneider et al., 2021], we can obtain this frequency profile assuming n=24 and m = 24, 25.

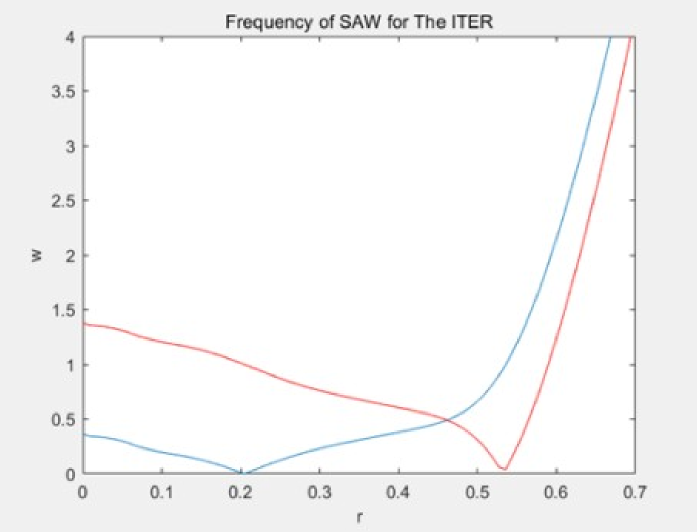

Fig. 9. Graph of frequency vs radius for the ITER

We can estimate a normalized frequency of TAE of $W_n = 0.49$

In the same way, we can obtain W_{TAE} as

$$\boldsymbol{W_{TAE}} = 116\ \boldsymbol{KHz} \sim 10^{5}\mathbf{Hz}$$

which is in good agreement with the numerical prediction of [T. Hayward-Schneider et al., 2021].

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[T. Hayward-Schneider, Ph. Lauber, A. Bottino and Z.X. Lu 2021] "Global linear and nonlinear gyrokinetic modelling of Alfven eigenmodes in ITER" T. Hayward-Schneider *et al* 2021 *Nucl. Fusion* 61 036045 (2021)

Section 9: The need of numerical simulations to understand the nonlinear plasma dynamics in a tokamak.

One of the open issues in the path to controlled nuclear fusion with magnetic confinement, is the anomalous transport of energy and particles from the tokamak core to the edge. This transport is due to the turbulence formed in the plasma by the nonlinear interaction of a sea of micro instabilities created by the density and temperature gradients. Due to this unwanted transport, it is more difficult to achieve the desired high temperatures in the plasma core and ignite the nuclear fusion. External heating mechanisms are used to increase the temperature in the core. These mechanisms produce suprasternal particles, named here energetic particles, which are supposed to thermalize and give their energy to the bulk plasma. Before the thermalization, energetic particles can excite electromagnetic macroscopic instabilities like Alfvén modes [Biancalani, A et al., 2021].

The ITER nuclear fusion project demands many big calculations which can be done with the help of supercomputers. This is a big project that requires testing and focus. The supercomputers will help with the numerical calculations and provide for us a test version of the nuclear fusion project. To ensure the success of future fusion devices, such as ITER, scientists can integrate data from smaller fusion device trials with enormous computer models to better comprehend the machine's requirements.

One important role for the theoretical modeling of the fusion plasmas is the numerical simulations that can be done with the help of the supercomputers. The modern supercomputer allows the scientific community to study Ab-initio simulations, with the goal of having a virtual tokamak [Sample, I. 2022], this means that it will allow us to create a virtual reproduction of the whole experiment which will help save money and create a wider understanding of the study. One supercomputer that can be used to make the calculations is the Marconi 100.

Fig. 10. MARCONI 100 is the new accelerated cluster based on IBM Power9 architecture and Volta NVIDIA GPUs, acquired by Cineca within PPI4HPC European initiative.

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Biancalani, A., et al. (2021). *Selfconsistent multiscale simulations of turbulence and energetic particles in tokamak plasmas*. Available at: *https://ppi4hpc.eu/news/selfconsistent-multiscale-simulations-turbulence-and energetic-particles-tokamak-plasmas*

Section 10: DEMO - What happens after ITER?

The DEMO demonstration power plant is planned as the successor to ITER. With the transition from ITER to DEMO, the convergence from a scientific and experimental programme to an industrial and technology-oriented programme will develop. A key criterion for DEMO's success is power generation. The Fusion community is working intensively on preparing the concept for DEMO. [EUROfusion, 2014]

Current fusion experiments are primarily aimed at understanding the properties and behaviour of plasmas. DEMO, on the other hand, aims to demonstrate that the technology developed can indeed be used to control plasma of unprecedented quality and, moreover, to generate electricity safely and continuously. It has also been shown that such a system can be maintained regularly, quickly, safely, and reliably. Another challenge in designing such a system is to balance the physical requirements with the technical and technological possibilities. DEMO's core requirement is to bring 300 MW to 500 MW of net electricity to the grid and to use a closed fuel cycle [EUROfusion, 2014].

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